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Advanced Applications of Smart Materials Research for the Enhancement of Australian Defence Capability

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ABSTRACT

Research and development (R&D) in advanced materials technology is being driven within the Australian Defence Science and Technology Organisation (DSTO) by requirements to enhance safety and survivability of platforms and personnel, along with requirements for enhanced maintainability and operability of platforms. The R&D in advanced materials is aimed at program delivery across the capability life-cycle. This paper focuses on advanced materials research in the forward-looking enabling R&D domain where the intersection of key technologies in areas such as nano and microtechnology, biotechnology, stealth materials, smart materials and structures, and energy generation and storage is being explored.

The paper presents three innovative projects which illustrate the range of technologies being addressed under the leading-edge DSTO Corporate Enabling Research Program (CERP) on Signatures, Materials and Energy. The enabling R&D projects outlined in this paper range between technology readiness levels from a program in smart sensors for structural health monitoring which is currently transitioning to field application, to longer-term, leading-edge development based on electromaterials for biomimetic actuation. A feature of each of the projects is strong external leveraging beyond DSTO to deliver challenging interdisciplinary S&T.

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Executive Summary

Advanced materials technology research and development (R&D) within the Australian Defence Science and Technology Organisation (DSTO) is driven by the requirements for increased safety and survivability of platforms and personnel, together with the requirements for enhanced platform maintainability and operability. The procurement of new acquisitions carries with it a requirement for innovative materials development and assessment in order to provide a technology-edge in those assets. There is a need for advanced armour materials to address asymmetric threats, especially to counter improvised explosive devices. Improved materials and processes are needed to meet demands for more effective through-life management and life extension of platforms. Advanced coatings technology is required to manage degradation control, particularly in the face of increased environmental regulation. Innovations in materials are also vital to assist in optimising energy management and usage.

This paper presents three innovative projects which illustrate the range of technological developments being addressed under the DSTO Corporate Enabling Research Program (CERP) on Signatures, Materials and Energy. These are (i) prototype development of sensors and associated systems to enable smart structural management based on prognostic health management of platforms on condition rather than through less efficient scheduled maintenance; (ii) enabling research on advanced materials processing to address generic materials degradation issues in some maritime platforms; and (iii) a much longer-range project to develop biomimetic actuation based on conducting polymers, and demonstrated in a miniature underwater device. A feature of the CERP program is external partnering and leveraging of interdisciplinary S&T—all three examples in this paper involve strong leveraging, including with industry (Austal and ASC Pty. Ltd.), the Australian Defence Materials Technology Centre (DMTC) and the Intelligent Polymer Research Institute (IPRI) at the University of Wollongong.

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1. Introduction

Significant research and development (R&D) investment in advanced materials technology is being driven within the Australian Defence Science and Technology Organisation (DSTO) by requirements to increase safety and survivability of platforms and personnel, along with requirements for enhanced maintainability and operability of platforms [1]. Innovative materials development and assessment are required to give a technology edge in new acquisitions. Advanced armour materials are required to address asymmetric threats, especially to counter improvised explosive devices. Improved materials and processes are needed to meet demands for more effective through-life management and life extension of platforms. Advanced coatings technology is required to manage degradation control, particularly in the face of increased environmental regulation. Innovations in materials are also vital to assist in optimising energy management and usage.

The DSTO R&D in advanced materials is aimed at application across the Defence capability life-cycle. This paper focuses on advanced materials research in the forward-looking enabling R&D domain where the intersection of key technologies in areas such as nano- and microtechnology, biotechnology, stealth materials, smart materials and structures, and energy generation and storage is being explored. The paper presents three innovative projects which illustrate the range of technology developments being addressed under the DSTO Corporate Enabling Research Program (CERP) on Signatures, Materials and Energy. The enabling R&D projects outlined in the paper range across the spectrum in terms of technology readiness levels, viz. (i) prototype development of sensors and associated systems to enable smart structural management based on prognostic health management of platforms on condition rather than through less efficient scheduled maintenance; (ii) enabling research on advanced materials processing to address generic materials degradation issues in some maritime platforms; and (iii) a much longer-range project to develop biomimetic actuation based on conducting polymers, and demonstrated in a miniature underwater device. A feature of the CERP program is external partnering and leveraging of interdisciplinary S&T—all three examples in this paper involve strong leveraging, including with industry (Austal and ASC Pty. Ltd.), the Australian Defence Materials Technology Centre (DMTC) and the Intelligent Polymer Research Institute (IPRI) at the University of Wollongong.

2. Sensors for Structural and Personnel Health Management

2.1 Sensors

DSTO sensor developments are targeted at applications in the broad areas of health management and corrosion, condition monitoring for large structures and personnel safety and environmental monitoring. Particular areas of interest include:

- Corrosion: detection of corrosion and corrosion rates; sensors to detect degradation due to corrosion, particularly in inaccessible areas and under paints and sealants
- Environmental monitoring: temperature, humidity, pressure
- Loads and strains: the development of alternative low-power sensing techniques to monitor loads and strains
- Acceleration and vibration: application of commercial micro-electro-mechanical systems (MEMS) sensors
- Chemical and biological sensors: the use of carbon nanotubes and molecularly imprinted plastics to develop sensors with high selectivity
- Infrared radiation: novel methods for the detection of infrared radiation
- Detection of microbiologically influenced corrosion (MIC) in maritime platforms.

Small size and weight has been an emphasis behind the development of these sensors, particularly for applications in aircraft or on personnel. Some effort has also been put into developing novel packaging concepts for suites of sensors. One of these is the integration of the sensor electronics and network interface with sensors for corrosion, wetness, temperature and humidity, into a single light weight (40 g) package [2] shown in Figure 1.

Figure 1: Corrosion, wetness, temperature and humidity sensors packaged with the interface and networking electronics into one small, low-power and light unit. This has been developed under a collaborative project with MiniFAB (Aust) Pty. Ltd., an SME based at Scoresby, Melbourne.

2.2 Sensor Interfacing and Networks

The interrogation of the sensors, such as those described above, requires sensitive electronics. For example, corrosion sensors, such as those developed for linear polarisation resistance (LPR) or electro-chemical impedance spectroscopy (EIS), have impedances in the range 10^{3}-10^{10} Ohm, and have strict requirements regarding the voltages that can be applied to the sensor (less than 20 milliVolts) to avoid driving corrosion on the sensor itself [2]. These are rather stringent requirements, and has necessitated the development of electronics interfaces to operate over these ranges. Again, an emphasis here has been low weight and size and, in addition, low-power operation. Specific sensor interface electronics have been developed and coupled with a universal, sensor invariant, network interface (or external interrogator) with common core system software, user interface and data protocols [3,4]. These are based around a low-power microcontroller that can have software loaded into it for particular sensors, and also offers large scope for on-sensor/interface data manipulation and storage. Particular aspects of this interface include:

- Long endurance when battery powered (particularly relevant for aircraft since corrosion may occur during periods when the airframe is powered down and also relevant for individual, personal sensors)
- Light weight and small size
- Software and hardware adaptability to accommodate new sensors
- Remote software upgrade ability, to avoid the need to physically access sensors as data processing algorithms are developed
- The ability to handle large networks of sensors, since networking can significantly reduce the wiring requirements
- Electrostatic discharge (ESD) protection
- A software interface that is flexible enough to accommodate single or multi sensor systems
- An architecture that allows simple or advanced data processing.

The network of sensors can then be managed by a network controller, such as an embedded PC, to continually gather data on the state of the structure that it is deployed in. A number of different interfaces for a range of different sensors and applications have been developed, all based on the same network interface. The sensor capabilities developed include:

- Measurement of AC impedance (amplitude and phase) from close to DC to greater than 400 kHz
- Measurement of DC resistance from 10^{-2} to 100's of Ohm (useful for mass loss sensors)
- Measurement of DC resistance from 10^{3} to 10^{10} Ohm (useful for electrochemical measurements)
- Measurement of currents from pA to mA
- Measurement of voltages from mV to 10's of Volt
- Interfacing to Commercial-Off-The-Shelf (COTS) sensors with any of the above as an output signal

- Interfacing to COTS sensors with digital serial outputs such as I2C, SPI, RS485 and RS232
- The corrosion sensor suite mentioned above (corrosion, wetness, temperature and humidity)
- Digital on/off sensors
- 3-axis strain gauge rosettes at up to 100 Hz data rates per axis
- 2 × 3-axis accelerometers at up to 100 Hz data rates per axis
- Remote temperature monitoring
- Measurement of paint/sealant/bond degradation using wire sensors [5].

Since all of these have the same network interface and core operating system firmware, a comprehensive network can be put together to monitor for corrosion, structural loads and other aspects of large operational platforms.

2.3 Industrial Sensing Applications

As an example, DSTO currently has a network of strain, acceleration and corrosion sensors installed on a Royal Australian Navy (RAN) Armidale Class Patrol Boat in a joint program with Austal, the boat's manufacturer [6,7]. This network consists of approximately 100 sensors located at 22 points throughout the vessel. The system monitors strain, acceleration and corrosion environments, and materials degradation continually. The acquired data will be used for life management of the aluminium-hulled boat, assessment over the life of the boat, and will inform future Defence acquisitions.

Through involvement in the Cooperative Research Centre for Integrated Engineering and Asset Management (CIEAM), DSTO has an active program to reduce asset through-life costs due to corrosion, and increase asset availability. This is achieved through the development and deployment of environment monitors and paint degradation sensors, combined with the development of coating degradation models to predict the time of coating failure, and corrosion prediction models to determine the residual life of structures and enable the setting of asset inspection intervals [8]. This work also includes innovations related to the maintenance of the Collins class submarine bilges and RAN ships, to minimise maintenance impacts associated with the potentially rapid spread of microbiologically influenced corrosion (MIC). The associated S&T program involves laboratory studies to understand and model the performance of a range of maritime materials subjected to MIC [9]. Also, a prototype electrical resistance MIC sensor is currently being trialled in a joint program with the ASC under CIEAM, in order to inform a future on-condition management strategy for the submarine.

3. Advanced Materials and Coatings

3.1 Fabrication of Nano- and Ultrafine Materials through Severe Plastic Deformation

The bulk production of nanostructured materials gives rise to the potential development of a new range of compositions having enhanced physical characteristics. The ability to refine alloys down to the nano-scale will potentially yield significant enhancements to mechanical properties. At the forefront in the top-down approach to the fabrication of the next generation of structural materials are the severe plastic deformation (SPD) material processing techniques of high pressure torsion (HPT) and equal channel angular pressing (ECAP) and their many variants. These techniques have enabled the fabrication of a range of nano- and ultrafine grained materials with various modifications to physical and mechanical properties.

At DSTO, HPT has been utilised to apply extreme shear strain to bulk materials for subsequent fundamental studies into the associated microstructural changes. One of the materials studied has been the as-cast Mn-Cu alloy Sonoston used in marine applications. This material was subjected to SPD to examine the effects on the coarse grained and heavily cored as-cast microstructure (Figure 2a). Coring, the non-uniform distribution of elements across a grain, occurs in Mn-Cu alloys upon solidification resulting in the formation of Mn-rich and Cu-rich regions. The difference in composition between regions has an adverse effect of corrosion properties and causes dealloying of Mn-rich regions when the alloy is exposed to seawater environments.

The depth of corrosion is strongly defined by the size of the cored regions and therefore also the grain size. HPT trials to-date show that as-cast material can be "homogenised", with the size of Mn and Cu-rich regions within the microstructure effectively reduced by the plastic flow and fragmentation of grains caused by the application of shear strain (Figure 2b). Corrosion studies on SPD material exposed to a 3.5% NaCl solution show the depth of dealloying is reduced from ~60 µm for as-cast material down to < 10 µm after SPD. Further work is planned to determine the grain size of the SPD material and to characterise the mechanical properties.

Nickel aluminium bronze (NAB) is employed widely in a variety of seawater systems contained within maritime platforms due to its high cavitation and corrosion resistance. The microstructure of NAB is complex and consists of up to 4 intermetallic phases (κ_1 to κ_4) within the α-matrix phase, and each phase possesses a discretely different composition due to their formation upon cooling (Figure 3a). It is anticipated that a refinement and redistribution of these phases, typically located adjacent to grain boundaries, will increase the crevice corrosion properties of NAB which is strongly influenced by the galvanic coupling between the intermetallic phases and the matrix when exposed to seawater.

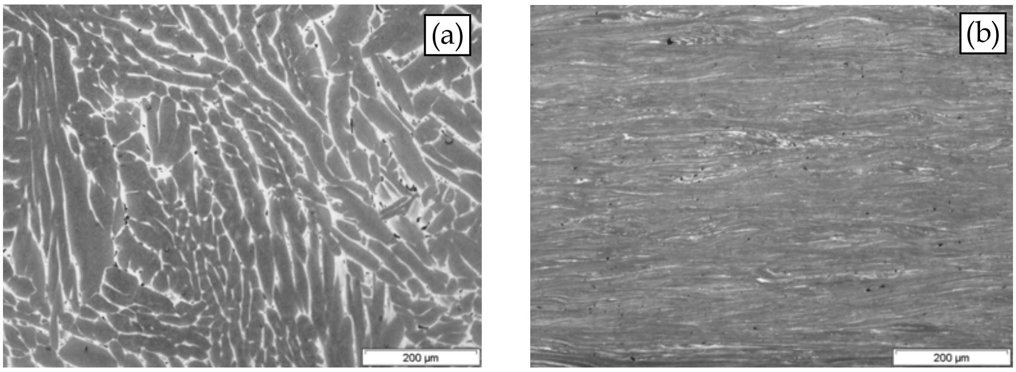

Figure 2: Optical micrographs of Mn-Cu alloy showing (a) coarse heavily cored as-cast structure (Mn-rich areas = grey) and, (b) alloy after being subjected to HPT strain ~64.

HPT studies have been carried out on as-cast NAB to examine the effect of shear strain and grain refinement on the various intermetallic phases size and distribution. Results to date indicate that refinement of the as-cast structure is feasible within a discrete range of HPT processing conditions (Figure 3b), although localized shear cracking, poor plastic flow and limited microstructural refinement were encountered in initial trials. These problems were largely overcome through changes to the processing parameters. Fragmentation and refinement of individual κ-phases within the NAB microstructure has yet to be quantitatively confirmed and will be part of a future work program aimed at increasing the applied strain, together with an examination of corrosion and mechanical properties.

Future work in this area includes the continued development of necessary infrastructure for the fabrication of ultrafine and nanostructured materials, and interaction with local academic and industry partners in these areas under the DMTC, as well potential application to other metals such as light alloys.

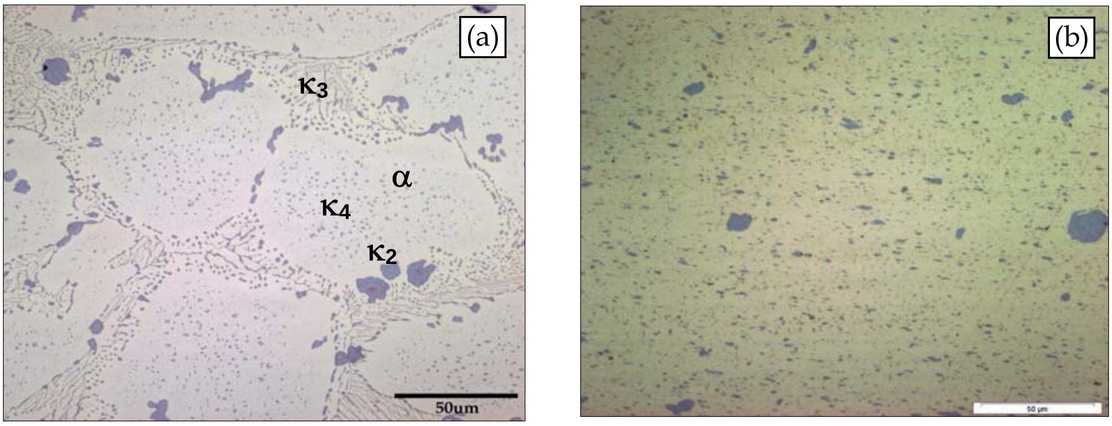

Figure 3: Optical micrographs of a nickel aluminium bronze material showing (a) the as-cast structure and the complex arrangement of intermetallic phases, and (b) material after HPT strain 128 with redistributed phases.

4. Energy Management

4.1 Miniature Unmanned Underwater Vehicle Actuation

The ability to conduct underwater inspections for various applications is of significant interest to Defence. Under the CERP, the use of electro-active materials (particularly polymers) as actuation sources in innovative small autonomous systems is being investigated. A key aspect of this work is the development of multi-actuation systems suitable for integration into a miniature covert autonomous underwater device ("smart fish") for future undersea missions. Of particular relevance is the assessment of payload limits for such devices.

A prototype robotic miniature underwater device powered using electrically conductive polypyrrole (PPy) artificial muscles and that embodies autonomous real-time control over the device's speed and direction of swimming has been developed jointly with the Intelligent Polymer Research Institute (IPRI) at the University of Wollongong [10]. The study has concentrated on the characterisation of a novel electromaterial muscle oscillator "tail fin" propulsor, used to generate forward movement on the robotic device. The maximum forward speed of 33 mm/s is the fastest reported speed for robotic fish powered by polymer actuators. The smallest turning radius of the device was 150 mm, or 1.1 body lengths. At its maximum speed, the miniature device operated at a Strouhal number of 0.28, which is within the optimum range identified from studies of several fish species.

While the prototype used (Figure 4) was based on previously-reported ostraciiform swimming robots powered by a single caudal fin, some aspects of this design were observed to limit swimming speed. In particular, it was observed that large tip amplitudes caused excessive turning of the "fish nose" away from the desired direction of travel. Nose turning increased the drag force and slowed fish speed. Hence, operating at larger tail amplitudes was counter-productive.

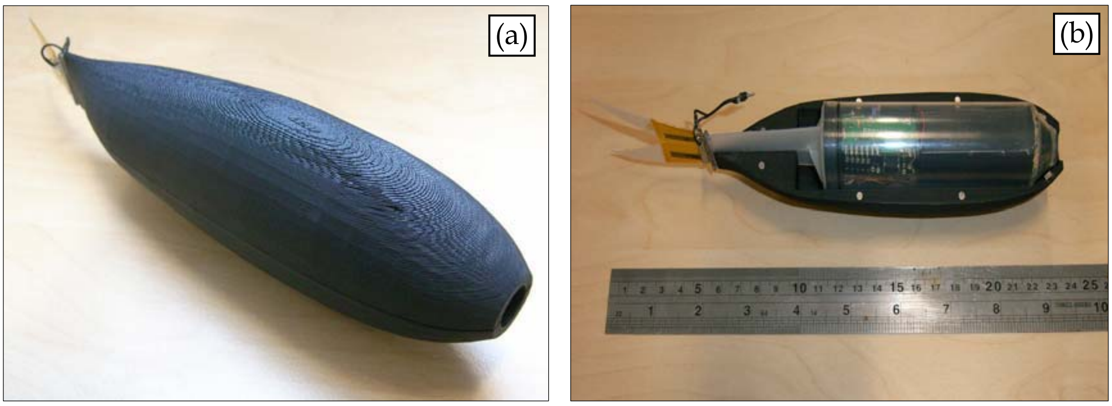

Figure 4: (a) A prototype miniature robotic fish using electrically conductive polypyrrole artificial muscle actuation for propulsion. (b) Internal structure of the fish. The body of the fish was made by a rapid prototyping method, courtesy of Prof Dermot Diamond, Dublin City University.

A major limitation of the PPy artificial muscle powered tail fin was the deterioration in its performance during extended immersion in water. A range of strategies are being considered to improve overall performance of the device. These include better encapsulating materials for the actuators that do not unduly stiffen the actuator and limit its bending. Further optimisations in the fin design and shape would also improve the thrust force generated from the PPy artificial muscle. A streamlining of the body shape would reduce drag on the system, allowing a much greater net propulsive force leading to faster movement. Miniaturisation of the electronics could reduce weight in the device, improving acceleration rates and / or increased payload. The optimal integration of various sensors is also being explored to facilitate autonomous underwater monitoring.

5. Conclusions and Future Directions

The three projects described in this paper, from the DSTO CERP on Signatures, Materials and Energy, are at varying stages of delivery into Defence capability. However, they all serve to illustrate the fact that innovations in advanced materials technology can give a technological edge to Defence capability. The overall CERP program spans applications across the capability life-cycle. Future S&T in this program will include leading-edge research in the management of ADF energy requirements, the continued development of smart materials and coatings technology for environmental degradation management, signature reduction and ballistic/blast protection, and a range of smart sensing applications. An increased focus will be given to the implementation of prognostics and health management in autonomous logistics systems – this will also require extensive modelling of associated damage mechanisms (particularly linked to corrosion) in order to implement maintenance decisions automatically. Challenges in the manipulation and management of large data sets and potential data fusion will also need to be addressed. External partnering to ensure ongoing technology transitioning will continue to be a major priority in the program.

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Smart Materials, Smart Sensors, Platform Availability, Capability, Maintainability

19. ABSTRACT

Research and development (R&D) in advanced materials technology is being driven within the Australian Defence Science and Technology Organisation (DSTO) by requirements to enhance safety and survivability of platforms and personnel, along with requirements for enhanced maintainability and operability of platforms. The R&D in advanced materials is aimed at program delivery across the capability life-cycle. This paper focuses on advanced materials research in the forward-looking enabling R&D domain where the intersection of key technologies in areas such as nano and microtechnology, biotechnology, stealth materials, smart materials and structures, and energy generation and storage is being explored.

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